REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0464

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1. REPORT DATE (DD-MM-YYYY)	2. REPORT DATE	3. DATES COVERED (From - To)
28/10/2003	final report	01/12/1999 - 30/11/2002

4. TITLE AND SUBTITLE

Development and Application of Molecular-Resolution Chemically-Sensitive Nanotube Probes

5a. CONTRACT NUMBER

5b. GRANT NUMBER

F49620-00-1-0084

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
4015 Wilson Blvd., Room 713
Arlington, VA, 22203-1954

10. SPONSOR/MONITOR'S ACRONYM(S)

AFOSR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release; distribution is unlimited.

20031117 007

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Carbon nanotubes have been developed as probes for molecular resolution atomic force microscopy imaging. Reproducible methods for the preparation of carbon nanotube probe tips by chemical vapor deposition were demonstrated, and moreover, approaches for the preparation of controlled diameter carbon nanotubes were defined. The utility of nanotubes probes was demonstrated with development of new method of nanofabrication, and with development of novel method for DNA sequence analysis. In addition, semiconductor nanowires have been developed as building blocks for nanophotonics. A new concept for a nanoscale photonic source using crossed nanowires was demonstrated, and the novel photonic properties of modulated nanowire heterostructures were shown for the first time.

15. SUBJECT TERMS

carbon nanotubes; atomic force microscopy; molecular imaging; nanofabrication; DNA; genetic analysis; nanowires; nanophotonics; light-emitting diodes; nanowire heterostructures.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		28	Mary Mitchell
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Final Technical Report for
GRANT NUMBER F49620-00-1-0084
1 December 1999 – 30 November 2002

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II. TECHNICAL REPORT

A. EXECUTIVE SUMMARY –

The overall objectives of our AFOSR funded research program have centered on the development of carbon nanotube atomic force microscopy (AFM) probes for ultrahigh resolution imaging and chemical sensitive imaging, as well as applying these probes to fundamental AFOSR problems, such as tribology and molecular detection. To achieve these objectives we have pursed several lines of research, including (1) the development of ultrasharp carbon nanotube probes, (2) preparation and use of modified nanotube probe ends for molecular-scale, chemically-sensitive imaging, and (3) measurement of intermolecular force potentials using modified probes.

In addition, we have broadened our objectives during the final year of the project to focus on exploring the development of a broad range of novel nanoscale photonic sources that could have wide ranging applications to AFOSR and DoD programs. To achieve these objective we have pursued the development of semiconductor nanowires with potential for optolectronic devices, have begun to characterize fundamental electrical and optical properties of these nanowire building blocks, and have assembled several proof-of-concept photonic devices.

B. COMREHENSIVE TECHNICAL SUMMARY

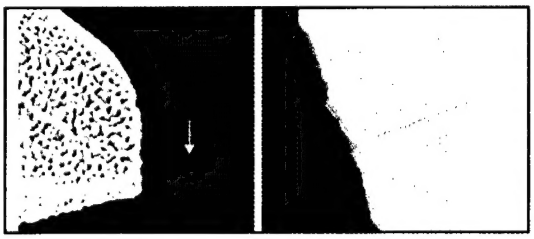
The major research objectives set forth in this AFOSR program were achieved during the project period, and moreover, significant new areas of science and technology were opened up as part of this effort. During the AFOSR project we successfully completed our proposed studies focused on the development of carbon nanotube probes as molecular resolution tips for scanning probe microscopies. Below we summarize the key findings from this work, including (i) the development of reproducible methods for the preparation of carbon nanotube probe tips by chemical vapor deposition and (ii) the development of methods to prepared controlled diameter carbon nanotubes. In addition, we made an unexpected advance by demonstrating the application of these technologies to DNA sequence analysis, and showed that this basic science could provide previously unavailable information. Lastly, we have made several advances in an exciting new area of nanoscale photonics that are also relevant to our current AFOSR program efforts. These advances included the demonstration of a new concept for a nanoscale photonic source—a crossed nanowire LED, the development of a general synthetic methodology for preparing nanowire structures in which the composition and/or doping are modulated along the wire axis, and the demonstration of novel photonic properties of modulated nanowire structures.

CVD growth of nanotube probe tips. Carbon nanotubes are materials that overcome many limitations that have hampered the use of atomic force microscopy (AFM) as a

high-resolution imaging technique in science and technology. Nanotubes consist of seamless cylinders made from sp^2-bonded carbon and in the case of single-walled nanotubes (SWNTs) consist of single, seamless cylinders of 0.5-5 nm diameter. The small radii and high aspect ratio of SWNTs have made them intriguing candidates for probe microscopy, although two additional properties of nanotubes, an extremely large Young's modulus (stiffness) and the ability to buckle elastically under large loads are essential to their use as probe tips. Our successful efforts placed on developing methods for the controlled growth of SWNT tips enabled a number of unique and in some cases unexpected science and technology applications during the course of our AFOSR project, including (i) molecular resolution structural imaging, (ii) biological application DNA sequence analysis for genomics, and (iii) a new approach for nanofabrication.

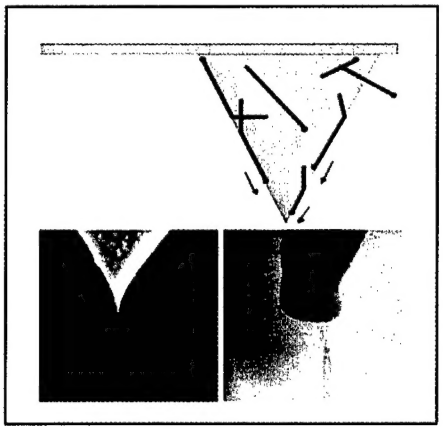
We developed two well defined methods for preparing nanotube tips that are based on metal-catalyzed chemical vapor deposition (CVD) during the AFOSR project. First, we have elucidate general approaches that enable direct CVD fabrication of nanotube probes with control of the size and orientation of the nanotube tip; these approaches are pore growth and surface growth.

The pore growth method utilizes nanopores created at the tip apex—for example by chemical etching or focused ion beam milling—to guide the growth of nanotube probes in an orientation ideal for imaging. Electrochemically or electrophoretically deposited iron in the nanopores catalyzes the selective CVD growth of nanotubes with an orientation controlled by the pores. Tips synthesized using the electrochemically deposited iron catalyst were shown to consist reproducibly of individual 3-5 nm radii MWNTs oriented optimally for high-resolution imaging. Significantly, these studies demonstrated for the first time that a well-defined synthetic approach could be used to prepare directly nanotube probes, thus opening the possibility of precise control over nanotube size and thereby tip resolution. A recent demonstration of this key point is the reproducible growth of SWNT tips having much smaller radii of only 1-3 nm using well-defined iron oxide nanocluster catalysts. These latter tips begin to approach the theoretical minimum size expected for individual SWNTs.



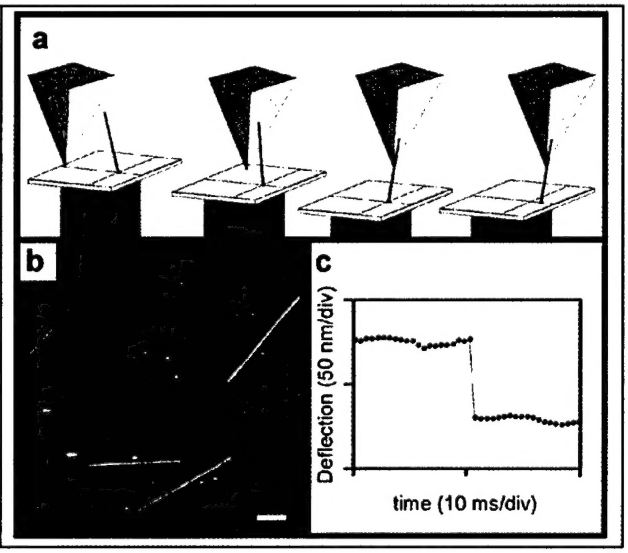
The surface growth method represents an attractive alternative to the above pore growth approach in that it exploits the power and control of CVD synthesis for nanotube tip preparation but dispenses with the need to create nanopores. In the surface growth method, competing nanotube-surface and nanotube bending energies self-direct the tip orientation during synthesis. A growing nanotube that reaches the pyramid edge at a glancing angle will bend if the attractive nanotube-surface interaction exceeds the energetic cost for bending. After bending the growing tube will follow the pyramid edge to the apex where it protrudes in an orientation ideal for imaging. Electron microscopy

studies have verified the essential details and reproducibility of the surface growth approach, and moreover, have shown that by lowering the catalyst density it is possible to produce well-defined individual SWNT tips. These studies have demonstrated the power of synthesis for controlling in a predictable manner the size of AFM tips at the molecular scale, and thus we believe represent a true break through for AFM imaging in biology. In addition, it is worth noting that these CVD tip growth methods are scaleable, in contrast to mechanical mounting, and could be implemented for large-scale production of AFM probes with sub-nanometer resolution.



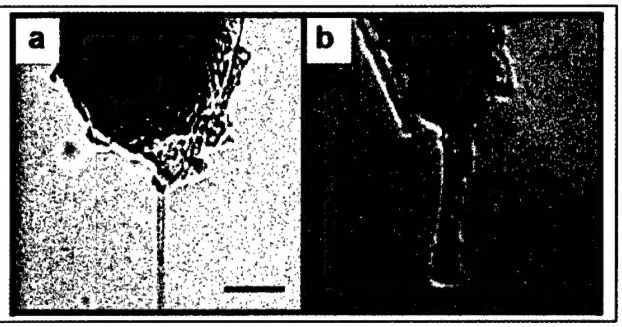
Our surface growth CVD represents a significant leap forward in probe preparation. This approach can also yield individual SWNT tips, which would represent the ultimate high-resolution probe, by lowering the catalyst density, although this strategy reduces the tip yield. To overcome this limitation we have recently developed a hybrid CVD/assembly method for the facile production of individual SWNT tips with essentially 100% yield. This new method is based upon the observation that microfabricated tips can 'pick up' vertically-aligned SWNTs from a planar substrate surface. Substrates with isolated, vertically aligned SWNT have been produced by CVD, and then microfabricated silicon tips are used to pick up individual SWNTs from the substrate during imaging to create well-aligned SWNT probes.

a) Schematic depicting the process by which a microfabricated pyramidal tip picks up a vertically aligned carbon nanotube. **b)** An AFM image of isolated, SWNTs on the substrate surface. The scale bar is 100 nm. **c)** A plot of the z-piezo position versus time for a single pick-up event demonstrating the pick-up event.



Definitive proof that the observed z-position jumps correspond to the attachment of individual SWNTs to the AFM tip apexes was obtained from TEM investigations. These TEM studies clearly show that (1) individual SWNTs are attached to the silicon tip

TEM images of **a)** a 0.9 nm diameter nanotube tip and **b)** a 2.8 nm diameter nanotube tip. The scale bars are 10 nm.

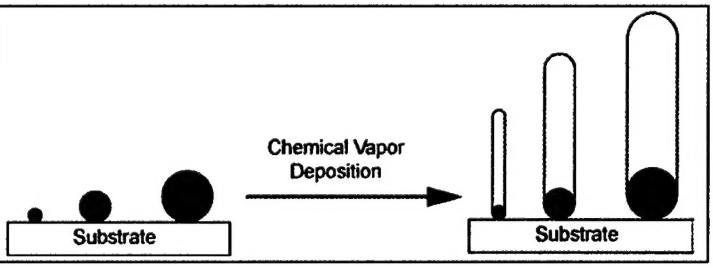


apexes, (2) the nanotube tips fabricated in this way are remarkably well aligned, and (3) the nanotube lengths extending from the tip apexes are similar to the z-position height steps. The range of SWNT diameters measured by TEM is also in good agreement with that measured by AFM for the nanotubes lying flat on the surface; that is, from 0.7 to 3 nm. The SWNT tips shown above illustrate this range with diameters of 0.9 and 2.8 nm, respectively.

Significantly, we have thus demonstrated a simple and high yield means of producing individual nanometer and sub nanometer diameter SWNT tips for AFM and other scanning probe microscopies. This straightforward method for preparing SWNT tips will enable widespread application of these ultrahigh resolution probes, in which the tip is essentially a single fullerene-like molecule, in many areas of science and technology. For example, these SWNT tips offer significant advantages for AFM applications in structural biology, and when modified at their ends, could enable spatially resolved functional imaging and single molecule force spectroscopy in which the reaction coordinate is well defined. In addition, this method could also be used to assembled SWNTs on advanced cantilever structures, which may not survive high CVD temperatures, such as those used for thermal sensing, to enable other types of experiments at unprecedented resolution.

Controlled Diameter Growth of Nanotubes. We have also developed a new method for the growth of controlled diameter nanotubes, which increases further the impact of our carbon nanotube probes and in addition will have a significant impact on carbon nanotube based research in general. In our reported synthetic method, the diameter size of CVD grown individual carbon nanotubes is controlled by the size of the pre-synthesized monodisperse iron nanoclusters. To enable this powerful approach we also had to

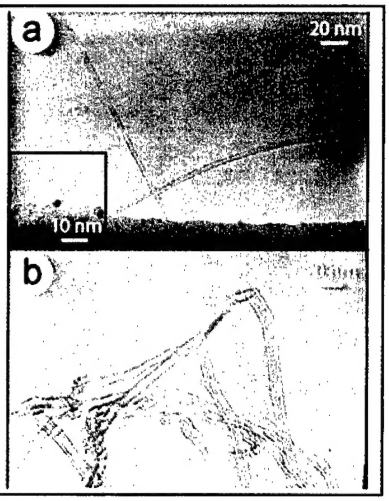
Schematic of diameter-controlled CVD growth of carbon nanotubes from different diameter iron catalyst nanoclusters.



develop a new and reproducible method for the synthesis of monodisperse iron nanocluster catalysts. This was achieved using different chain length alkanoic acids to coordinate to and limit the growth of iron nanoclusters formed from the homogeneous

decomposition of $Fe(CO)_5$. Specifically, we have found that as the organic chain length increases from 8 carbon atoms (octanonic acid), to 12 carbon atoms (lauric acid) to 18 carbon atoms (oleic acid), the iron nanocluster particle diameters decrease from 12.6 +/- 1.7, 9.0 +/- 0.9, to 3.2 +/- 0.8 nm. In all cases, the nanoclusters exhibit narrow diameter distributions characteristic of nearly monodisperse particles.

Significantly, we have used these catalysts in a CVD growth process to demonstrate clearly that carbon nanotubes with diameters defined by the sizes of catalytic clusters can be prepared. Iron nanoclusters with diameters of 3, 9 and 13 nm have yielded carbon nanotubes with mean diameters of ca. 3, 7 and 12 nm, respectively. In addition, transmission electron microscopy has shown in all cases that the nanotubes are of high quality. The ability to produce carbon nanotubes of different sizes over an order of magnitude opens up a number of exciting opportunities. First, this advance will enable studies of the effects of nanotube diameter on the fundamental properties, such as electrical transport and mechanical properties of carbon nanotubes. Second, the availability of different diameter nanotubes has also enabled us to begin studying the



TEM micrographs of carbon nanotubes grown from (a) 3 and (b) 9 nm diameter iron nanoclusters. The inset in (a) shows the initial stage of carbon nanotube growth (short tube) with both nanocluster catalyst and tube clearly visible. The nanotube diameters in (a) 2.6 +/- 0.8 nm and (b) 7.3 +/- 2.2 nm are close to those of the catalyst clusters.

nanomechanical properties of organic layers, such as bilayers, which has opened up an exciting collaboration with theorist. Lastly, large diameter carbon nanotubes have the potential for use as "nanostraws", and could thus be used for transporting and depositing materials in nanolithography, and as templates for the synthesis of new materials.

Nanostructure Fabrication. We have also shown that these well-defined SWNT tips can be used to fabricate nanotube-based nanostructures by controlled deposition of segments of the tips in defined patterns. To deposit a SWNT segment in a specific location, the tip is first biased at the starting point, and then scanned along a set path. To complete the deposition, a voltage pulse is used to disconnect the tip from the nanotube segment on the substrate. This method has been
used to produce very straight structures, since we do not need to overcome tube-surface forces during deposition, and to create crossed SWNT-SWNT electronic devices. Our approach offers significant advantages compared to other methods that have been used to fabricate SWNT devices. Previous methods have been limited in part by chance (of getting a suitable tube on or near electrodes), potential tube damage caused by AFM manipulation, and a difficulty in knowing the SWNT electronic properties prior to making electrical connections. With our nanotube tip deposition method, we can control

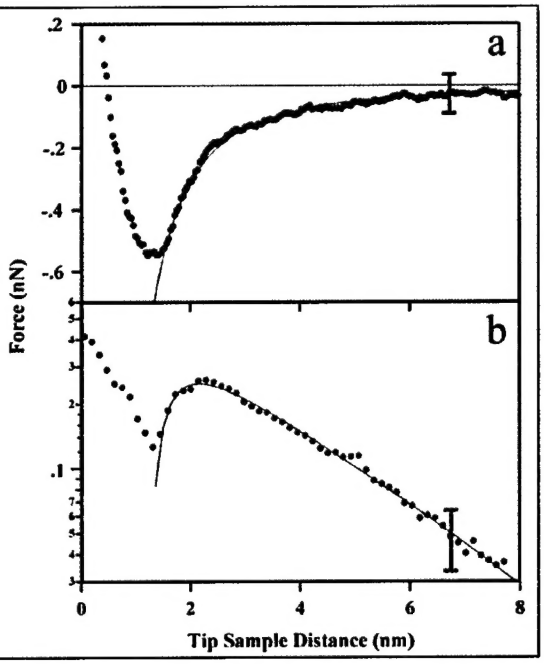
the precise spatial location and size of deposited nanotubes, and to a large extent the electronic properties of the deposited tube. Specifically, current-voltage measurements made prior to deposition can be used to determine whether the SWNT is metallic or semiconducting, and thus tips having the required properties can be used selectively in the fabrication.

Measurement of Intermolecular Potentials. The AFM can probe forces between a tip and sample with high sensitivity and spatial resolution in solution, and thus can provide information critical to understanding potential energy surfaces through the measurement of force profiles. A force profile is the derivative of a one-dimensional projection of the potential energy surface, where the reaction coordinate is defined by the pulling direction. The potential energy surface, which determines both energetics and dynamics of the reaction, can then be reconstructed by integration. Unfortunately, in most AFM experiments there exists a region in the potential energy surface where the derivative of the force profile (second derivative of the potential energy surface) exceeds the stiffness of the AFM cantilever. This condition causes the tip to snap to contact during approach and snap out during separation, thus precluding measurement of the attractive portion of the potential at small separations.

To overcome this substantial limitation and thereby provide new information critical to many areas of AFOSR research, we have been developing methods to determine the full potential of mean force. In particular, we have developed magnetic force feedback spectroscopy to measure mean potential of interaction between surfaces on a nanometer scale. Magnetic feedback is effective in removing the instability associated with force profile measurements with soft springs. A characteristic approach curve with magnetic feedback off for hydroxyl-terminated self-assembled monolayers (SAMs) on the tip and sample surfaces show the typical instability associated with the tip snapping to contact with the sample when it enters the steep region of the potential surface. To map continuously the force profile requires that the cantilever stiffness be greater than the steepest gradient in the force profile. The magnetic feedback has enabled us to increase the stiffness and achieve this goal.

We have used the MF-CFM data to analyze the interaction between the hydroxyl-terminated and carboxyl-terminated tip and sample surfaces. The long range attractive region of the force profiles for hydroxyl terminated surfaces was well fit by an inverse square power law expected for the van der Waals interaction and provided a value for the critical Hamaker constant. The MF-CFM data also extends to chemically relevant short-range attractive interactions and contact, although more detailed models must be developed to utilize this data. Similar results were also obtained on the chemically complex carboxyl terminated surfaces demonstrating the versatility of our approach. Moreover, MF-CFM experiments with nanotube tips should enable force profiles of complex systems along well-defined projections of the potential surface to be obtained, and we expect that such experiments will have a far-reaching impact on chemistry and biology.

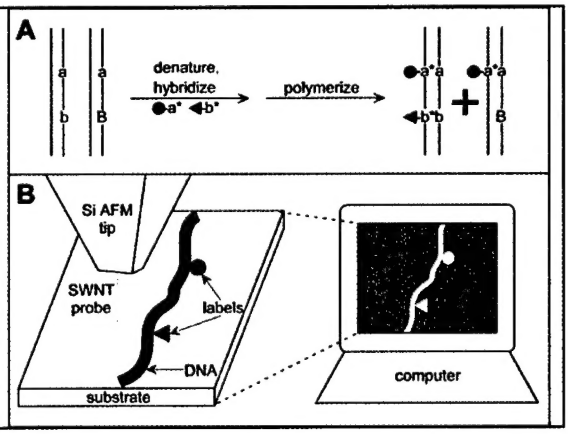
Force profiles for (a) hydroxyl-terminated SAMs in deionized water and (b) carboxyl terminated SAMs in 0.010 M, pH 7 phosphate buffer. Both profiles were recorded while approaching the sample to the tip. Experimental data are red solid circles and fits are solid blue lines. The error bars in (a) and (b) are representative of the respective data sets.



DNA Sequence Analysis. Another area where we have made an unexpected impact with the nanotube probes developed in our AFOSR project is DNA analysis. The Human Genome Project is now providing massive amounts of genetic information that should revolutionize the understanding and diagnosis of inherited diseases, and similar efforts for other organism could provide information critical to the identification of bio-threats to defense. To make this information most useful, however, will require new technologies capable of rapidly cataloging of single nucleotide polymorphisms (SNPs) in gene coding and regulatory regions, and capable of the haplotype of a subject—the specific alleles associated with each chromosome homologue.

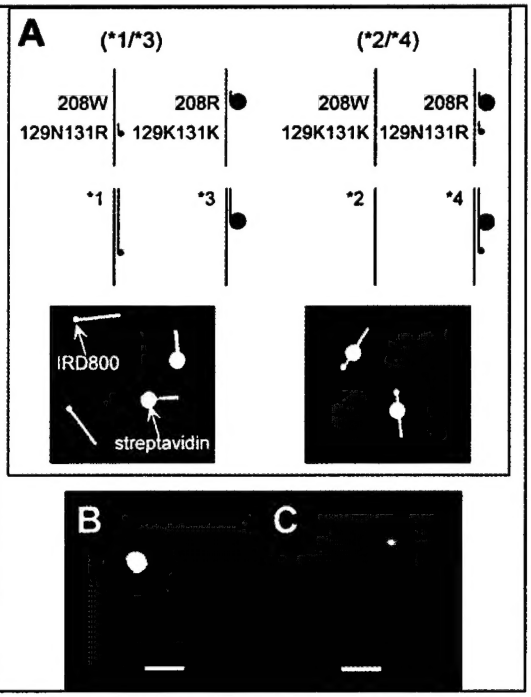
We have recently developed a simple, yet elegant new approach to DNA sequence analysis and haplotyping that involves direct visualization of polymorphic sites on individual DNA molecules. Our method utilizes AFM with high-resolution carbon nanotube probes to read directly multiple polymorphic sites in DNA fragments containing from ca. 100 to at least 10,000 bases as illustrated below. In this method,

Schematic illustration of the method for labeling specific DNA sites and detection with SWNT AFM probes. **A**, Labeled oligonucleotide probes (●-a* and ◀-b*) are specifically annealed to their complementary target sequences (a and b) but not to sequences with a single-base mismatch (A and B) in the single-stranded DNA template. **B**, The presence and locations of the sequence specific tags (● and ◀) can be readily observed in the AFM image.



labeled oligonucleotide probes are used to target sequences in DNA fragments, followed by direct reading of the presence and spatial locations of the labels by AFM. The nanotube tips, which can be reproducibly prepared with tip radii less than 3 nm and ca. 10 base resolution, enable high resolution, multiplex detection of different labels.

Our new method has been demonstrated by identifying the spatial location of specific sequences with excellent discrimination from corresponding single-base mismatches in the M13mp18 plasmid using seven base oligonucleotide probes. By using different size probes molecules, we have also shown that this approach enables multiplexed sequence detection in large DNA strands, and thus opens the possibility for profiling multiple polymorphic sites on DNA fragments in the 10 kilobase or larger size range. To illustrate this critical point, we have determined haplotypes on a UDP-glucuronosyltransferase gene, UGT1A7, whose enzyme product is involved in inactivation of carcinogens such as benzo[a]pyrene metabolites. This gene has two polymorphic sites (separated by 233 bp) that determine four alleles, each specifying different polypeptide chains.



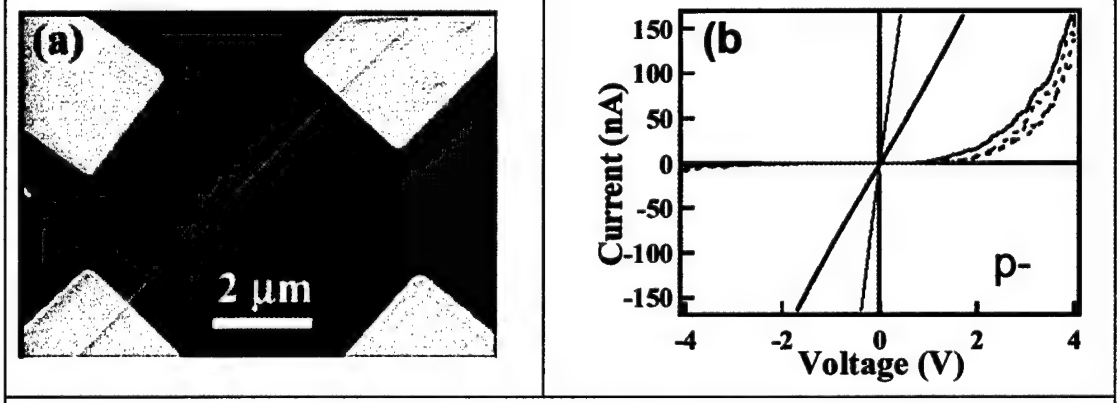
Direct haplotyping of UGT1A7 using SWNT probes. **A**, Schematic showing haplotypes, alleles, genotypes, and locations of probes in samples analyzed. The (*1/*3) and (*2/*4) haplotypes, which have the same genotype (heterozygous at both loci), are specifically labeled at the 129N131R and 208R sites with IRD800 (small filled circle) and streptavidin (large filled circle), respectively. **B**, Representative nanotube image of the *3 allele (streptavidin end-labeled, ~140 nm DNA) detected in a sample that was heterozygous at both loci. **C**, Nanotube image of the *1 allele (IRD800 end-labeled, ~210 nm DNA) detected in the same sample as **B**.

Importantly, individuals who are heterozygous at both sites have a single genotype, but one of two haplotypes, (*1/*3) or (*2/*4), which cannot be differentiated using conventional methods. This ambiguity is crucial in screening, since each allele exhibits substantially different enzymatic activity towards targeted carcinogens. Significantly, subject samples could be unambiguously shown to exhibit the (*1/*3) haplotype by direct inspection of AFM images as shown above.

Direct DNA sequence analysis and haplotyping with carbon nanotube tips represents a significant advance over conventional approaches and could facilitate high-throughput screening of single nucleotide polymorphisms for association and linkage studies of inherited diseases and genetic risk. In addition to applications in population-based genetic disease studies, this approach could serve as a new method for rapid DNA identification of emerging bio-threats required urgently by the DoD.

Crossed nanowire nanoscale light emitting diodes. The availability of well-defined n-and p-type nanowire building blocks has opened up the possibility of creating complex functional devices by forming junctions between two or more wires. To explore this new concept, we have studied the transport behavior of n-n, p-p and p-n junctions formed by crossing n-type and p-type nanowires. Electrical transport data recorded on the individual nanowires in n-n and p-p crossed junctions show linear or nearly linear behavior, indicating that the metal electrodes used in the experiments make ohmic contact to the nanowires. This point is important since it shows that the nanowire-metal contacts will not make nonlinear contributions to the measurements across the nanoscale junctions. In general, transport measurements recorded across the n-n and p-p junctions show linear behavior. These results indicate that interface oxide between individual nanowires does not produce a significant tunneling barrier since a tunneling barrier would lead to highly non-linear behavior. Taken as a whole, these data show that individual nanowires can make good electrical contact with each other, despite the small contact area (10^{-12}-10^{-10} cm^2) and simple method of junction fabrication.

Studies designed to probe the utility of this new approach for creating functional devices were focused on p-n junctions from crossed p- and n-type nanowires since the p-n junction forms the basis for the critical photonic devices, including LEDs and lasers. These junctions can be made reproducibly by sequential deposition of dilute solutions of n- and p-type nanowires with intermediate drying. Typical transport behavior of crossed InP nanowire p-n junctions show linear I-V for the individual n- and p-type nanowires,

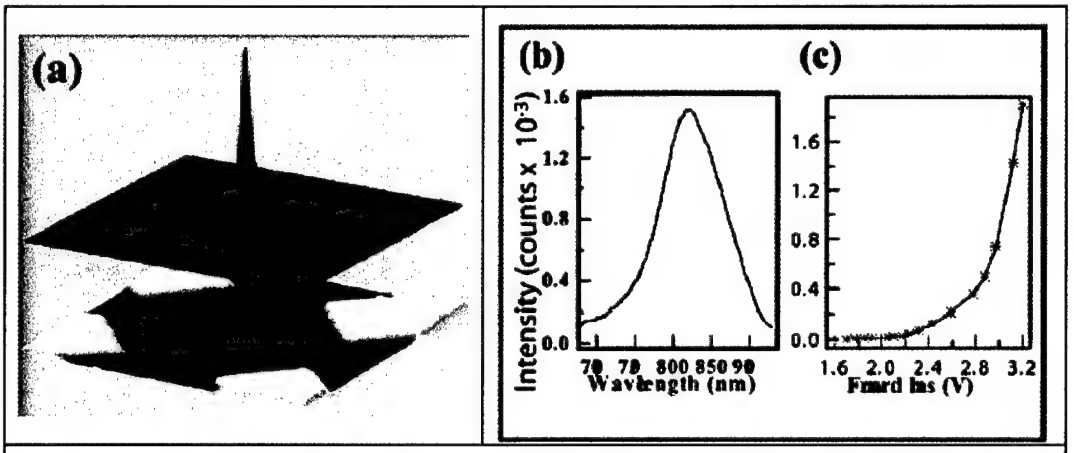


Crossed nanowire junctions. (a) SEM image of a crossed InP device with metal electrodes contacting each of the four arms. (b) I-V behavior of a p-n junction. The lines represent transport behavior across pairs of adjacent arms.

which indicates ohmic contacts, while transport across the p-n junction shows clear current rectification. Specifically, little current flows in reverse bias, while there is a sharp current onset in forward bias. Significantly, this behavior is similar to conventional semiconductor p-n junctions, which form the basis for photonic devices.

To assess such function in our nanoscale devices, we studied the photoluminescence (PL) and electroluminescence (EL) from crossed nanowire p-n junctions. Significantly,

EL can be readily observed from these nanoscale p-n junctions in forward bias. A PL image of a crossed nanowire junction shows a crossed wire-like structure, and

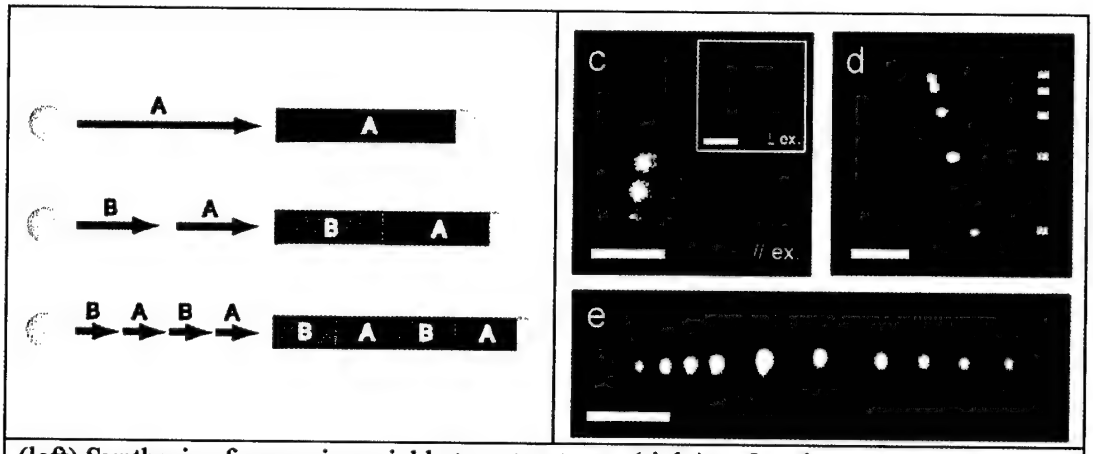


Crossed nanowire LED. (a) (top) Three-dimensional (3D) plot of light intensity of the electroluminescence from a crossed nanowire device. Light is only observed at the cross point. (bottom) AFM image of the device. (b) Spectrum of the emission shows a peak at ca. 820 nm. (c) Plot of integrated intensity versus forward bias voltage.

comparison of the EL and PL images shows that the position of the EL maximum corresponds to the crossing point in the PL image, thus demonstrating that the light originates from the nanowire p-n junction. Characterization of the EL intensity as a function of forward bias of the junction shows that significant light can be detected with our system at a voltage as low as 1.7 V. Further increases in forward bias beyond this 'turn-on' voltage produce rapid, increase in the EL intensity. In addition, EL spectra recorded from the crossed nanowire LEDs exhibit blue shifts relative to the bulk band gap of InP (925 nm), which are due in part to quantum confinement of excitons. Significantly, recent PL studies of individual InP nanowires demonstrated that the PL peak can be systematically blue-shifted as the nanowire diameter is decreased, and thus these results provide a means for controlling the color of the LEDs in a well-defined way. Theability to tune color with size might be especially useful in the future nanophotonic applications. In our proposed studies outlined below, we plan to extend significantly the concept of the crossed nanowire nanoLED to enable multicolor emitters and arrays.

Axial nanowire photonic heterostructures. Intricate n- and p-type and more generally compositionally modulated (i.e., superlattice) structures are used in the planar semiconductor industry to enable versatile electronic and photonic functions. To expand the function possible in semiconductor nanowires we have been exploring the growth of axial superlattices in which the composition and/or doping are modulated along the length of the nanowire. In this regard, we have recently made a break-though in demonstrating a potentially general approach to the synthesis of semiconductor nanowire superlattices from group III-V and group IV materials, and have shown that these new nanowire materials can provide novel photonic properties.

Our approach to superlattice growth exploits recent developments in metal catalyzed nanowire synthesis, which have shown that nearly monodisperse metal nanoclusters can be used to control the diameter and through growth time the length of semiconductor



(left) Synthesis of nanowire axial heterostructures. (right) **c, d** and **e** are photoluminescence images of 3, 5 and 10 period GaAs/GaP superlattice structure, respectively.

nanowires via a vapor-liquid-solid growth process. We have introduced the vapor phase semiconductor reactants required for nanowire growth by either laser ablation of solid targets or vapor phase molecular species. To create a single junction within the nanowire, the addition of the first reactant is stopped during growth, and then a second reactant is introduced for the remainder of the synthesis; repeated modulation of the reactants during growth produces nanowire superlattices. This approach can be successfully implemented when a nanocluster catalyst suitable for growth of the different superlattice components under similar conditions is used.

Significantly, we have shown that this approach can produce compositionally modulated nanowire superlattices in which the number of periods and repeat spacing are readily varied during growth. TEM images of a six period structure corresponding to a $(GaP/GaAs)_3$ superlattice have shown that the 20 nm diameter nanowires are highly uniform over their ca. 3 μm lengths. Spatially resolved EDS measurements of composition further demonstrate that the P and As regions are distinct from one another and that there is minimal cross-contamination. Moreover, these data show that each GaP and GaAs nanowire segment has a length of about 500 nm, and are thus consistent with the equal growth times used for each segment but also show that growth rates remain relatively constant during the entire nanowire synthesis.

The GaAs/GaP nanowire superlattices are also an attractive system for nanophotonic applications since GaAs is a direct band gap semiconductor, while GaP has an indirect gap. Indeed, photoluminescence (PL) imaging of individual nanowires from the $(GaP/GaAs)_3$ superlattice sample described above shows that these nanowires exhibit an emission pattern of three spots separated by dark regions. This pattern is consistent with emission originating from the three GaAs regions, separated by dark GaP regions that act as optically inactive "spacers." In addition, we have used single nanowire PL studies as a metric of the level of control possible in nanowire superlattice growth by our new approach. Specifically, we find that systematic variations in the growth time produces nanowire superlattices with well-defined changes in periodicity as demonstrated by the PL images of a 11-layer superlattice in which the length of the GaP regions was doubled each layer while maintaining a constant GaAs period, and the image of a 21 layer

GaP/GaAs superlattices consisting of a short 4 period (GaP/GaAs) repeat, followed by 3 longer GaP spacer repeats, and ending in a relatively short 4 period (GaAs/GaP) repeat.

We believe that these nanowire superlattice structures could serve as important building blocks for photonic applications. For example, these materials could serve as optical nano-barcodes. Moreover, the wide range of group III-V and II-VI nanowires that have been demonstrated in our previous work suggests that it should be possible to encode additional information through variations in the color of the emitting region using multi-component superlattices. Using materials with a large dielectric contrast might also enable the creation of 1D waveguides with built-in photonic band gaps, or as cavities for nanowire lasers. We will explore these new directions as part of our proposed studies.

C. PERSONNEL INVOLVED IN RESEARCH EFFORT

Charles M. Lieber, Principal Investigator
Linda Ross, Laboratory Administrator
Paul Ashby, Graduate Student, Ph.D. received 5/03.
Yi Cui, Graduate Student, Ph.D. received 9/02.
Teri Wang Odom, Graduate Student, Ph.D. received 11/00
Qingqaio Wei, Graduate Student, Ph.D. received 9/01.
Yue Wu, Graduate Student, current.

D. PH.D THESES STEMMING FROM RESEARCH EFFORT

Paul Ashby, "Intermolecular and Interfacial Forces: Elucidating Molecular Mechanisms using Chemical Force Microscopy"

Yi Cui, "Semiconductor Nanowires for Nanotechnology: Synthesis, Properties, Nanoelectronics, Nanophotonics, and Nanosensors"

Teri Wang Odom "Electronic Properties of Single-walled Carbon Nanotubes"

Qingqaio Wei, "Synthesis, Properties and Applications of Nanorods and Nanowires"

E. PUBLICATIONS STEMMING FROM RESEARCH EFFORT

REFEREED JOURNAL ARTICLES:

1. A. Yazdani and C.M. Lieber, "Up close and personal to atoms", *Nature* **401**, 227-230 (1999).
2. J.H. Hafner, C.L. Cheung and C.M. Lieber, "Direct Growth of Single-Walled Carbon Nanotube Scanning Probe Microscopy Tips", *J. Am. Chem. Soc.* **121**, 9750-9751 (1999).
3. J. Wang, K.C. Rose and C.M. Lieber, "Load-Independent Friction: MoO_3 Nanocrystal Lubricants", *J. Phys. Chem. B* **103**, 8405-8409 (1999).

4. P. Kim and C. M. Lieber, "Nanotube Nanotweezers", *Science* **286**, 2148 - 2150 (1999).

5. T.W. Odom, J.-L. Huang, P. Kim and C.M. Lieber, "Structure and Electronic Properties of Carbon Nanotubes", *J. Phys. Chem. B* **104,** 2794-2809 (2000).

6. C.L. Cheung, J.H. Hafner and C.M. Lieber, "Carbon Nanotube Atomic Force Microscopy Tips: Direct Growth by Chemical Vapor Deposition and Application to High-Resolution Imaging", *Proc. Nat. Acad. Sci. USA* **97**, 3809-3813 (2000).

7. C.L. Cheung, J.H. Hafner, T.W. Odom, K. Kim and C.M. Lieber, "Growth and Fabrication with Single-Walled Carbon Nanotube Probe Microscopy Tips" *Appl. Phys. Lett.* **76**, 3136-3138 (2000).

8. A.T. Woolley, C. Guillemette, C.L. Cheung, D.E. Housman, and C.M. Lieber, "Direct haplotyping of kilobase-size DNA using carbon nanotube probes" *Nat. Biotechnol.* **18**, 760-763 (2000).

9. P.D. Ashby, L. Chen and C.M. Lieber, "Probing Intermolecular Forces and Potentials with Magnetic Feedback Chemical Force Microscopy" *J. Am. Chem. Soc.* **122**, 9467-9472 (2000).

10. A.T. Woolley, C.L. Cheung, J.H. Hafner and C.M. Lieber, "Structural Biology with Carbon Nanotube AFM Probes", *Chem. Biol.* **7**, R193-R204 (2000).

11. T.W. Odom, J.L. Huang, C.L. Cheung, and C.M. Lieber, "Magnetic Clusters on Single-Walled Carbon Nanotubes: The Kondo Effect in a One-Dimensional Host" *Science* **290,** 1549-1552 (2000).

12. M. Bockrath, W. Liang, D. Bozovic, J.H. Hafner, C.M. Lieber, M. Tinkham, and H. Park, "Resonant Electron Scattering by Defects in Single-Walled Carbon Nanotubes" *Science* **291**, 283-285 (2001).

13. J. Hafner, C.L. Cheung, T.H. Oosterkamp, and C.M. Lieber, "High Yield Assembly of Individual Single-Walled Carbon Nanotube Tips for Scanning Probe Microscopies" *J. Phys. Chem. B* **105,** 743-746 (2001).

14. A. Jorio, R. Saito, J. H. Hafner, C.M. Lieber, M. Hunter, T. McClure, G. Dresselhaus, and M.S. Dresselhaus , "Structural (n, m) Determination of Isolated Single-Wall Carbon Nanotubes by Resonant Raman Scattering" *Phys. Rev. Lett.* **86**,1118-1121 (2001).

15. J.H. Hafner, C.L. Cheung, A.T. Woolley, and C.M. Lieber, "Structural and functional imaging with carbon nanotube AFM probes" *Progr. Biophys. Mol. Biol.* **77**, 73-110 (2001).

16. C.M. Lieber "The Incredible Shrinking Circuit" *Sci. Am.*, **285**, 50-56 (2001).

17. G.R. Schnitzler, C.L. Cheung, J.H. Hafner, A.J. Saurin, R.E. Kingston, and C.M. Lieber "Direct Imaging of Human SWI/SNF Remodeled Mono- and Polynucleosomes by Atomic Force Microscopy Employing Carbon Nanotube Tips," *Mol. Cell. Biol.* **21**, 8504-8511 (2001).

18. E.T. Powers, S.I. Yang, C.M. Lieber, and J.W. Kelly "Ordered Langmuir-Blodgett Films of Amphiphilic β-Hairpin Peptides Imaged by Atomic Force Microscopy," *Angew. Chem. Int. Ed.* **41**, 127-130 (2002).

19. M.S. Gudiksen, L.J. Lauhon, J. Wang, D. Smith, and C.M. Lieber "Growth of Nanowire Superlattice Structures for Nanoscale Photonics and Electronics," *Nature* **415**, 617-620 (2002).

20. C.M. Lieber "Nanowire Superlattices," *Nano Letters* **2**, 81-82 (2002).

21. Y. Huang, X. Duan, Y. Cui, and C.M. Lieber "Gallium Nitride Nanowire Nanodevices," *Nano Letters* **2**, 101-104 (2002).

22. C.L. Cheung, A. Kurtz, H. Park, and C.M. Lieber "Diameter Controlled Synthesis of Carbon Nanotubes," *J. Phys. Chem B* **106**, 2429-2433 (2002).

23. L. Chen, K.A. Haushalter, C.M. Lieber, and G.L. Verdine "Direct Visualization of a DNA Glycosylase Searching for Damage," *Chem. Biol.* **9**, 345-350 (2002).

24. D.V. Vezenov, A.V. Zhuk, G.M. Whitesides, and C.M. Lieber "Chemical Force Spectroscopy in Heterogeneous Systems: Intermolecular Interactions Involving Epoxy Polymer, Mixed Monolayers and Polar Solvents," *J. Am. Chem. Soc.* **124**, 10578-10588 (2002).

25. C.M. Lieber "Nanoscience and Nanotechnology: Building a Big Future from Small Things" *Update.* New York, NY: New York Academy of Sciences, October 2002, p.6-9.

26. D.V. Vezenov, A.V. Zhuk, G.M. Whitesides, and C.M. Lieber "Chemical Force Spectroscopy in Heterogeneous Systems: Intermolecular Interactions Involving Epoxy Polymer, Mixed Monolayers and Polar Solvents," *J. Am. Chem. Soc.* **124**, 10578-10588 (2002).

27. C.M. Lieber "Nanoscience and Nanotechnology: Building a Big Future from Small Things" *Update.* New York, NY: New York Academy of Sciences, October 2002, p.6-9.

28. L.J. Lauhon, M.S. Gudiksen, D. Wang, and C.M. Lieber "Epitaxial Core-Shell and Core-Multi-Shell Nanowire Heterostructures," *Nature* **420**, 57-61 (2002).

29. E. Joselevich, and C.M Lieber, "Vectorial Growth of Metallic and Semiconducting Single-Wall Carbon Nanotubes" *Nano Letters* **2**, 1137-1141 (2002).

30. X. Duan, Y. Huang, R. Agarwal, and C.M. Lieber, "Single-Nanowire Electrically Driven Lasers" *Nature* **421**, 241-245 (2003).

31. Z. Zhong, F. Qian, D. Wang, and C.M. Lieber, "Synthesis of p-Type Gallium Nitride Nanowires for Electronic and Photonic Nanodevices" *Nano Letters* **3**, 343-346 (2003).

32. C.M. Lieber, "Nanoscale Science and Technology: Building a Big Future from Small Things" *MRS Bulletin*, **28**, 486-491 (2003).

33. C. J. Barrelet, Y. Wu, D. C. Bell and C. M. Lieber; "Synthesis of CdS and ZnS Nanowires Using Single-Source Molecular Precursors" *J. Am. Chem. Soc*, **125**, 11498-11499 (2003).

BOOKS/BOOK CHAPTERS

1. T.W. Odom, J.H. Hafner, and C.M. Lieber, "Scanning Probe Microscopy Studies of Carbon Nanotubes", in *Topics Appl. Phys., M.S. Dresselhaus*, G. Dresselhaus, P. Avouris, (Eds)., 80, 175-213 (Springer-Verlag, 2001).

2. X. Duan, Y. Huang, Y. Cui, and C.M. Lieber, "Nanowire Nanoelectronics Assembled from the Bottom-Up" in *Molecular Nanoelectronics,* M. Reed and T. Lee, eds. (American Scientific Publishers, 2003). (Accepted for publication).

3. X. Duan, Y. Huang, Y. Cui and C.M. Lieber, "Nanowire Nanoelectronics Assembled from the Bottom-Up" in *Molecular Nanoelectronics,* M. A. Reed and T. Lee (Eds.) 199-227 (American Scientific Publishers, 2003).

4. Y. Cui, X. Duan, Y. Huang, and C.M. Lieber, "Nanowires as Building Blocks for Nanoscale Science and Technology," in *Nanowires and Nanobelts – Materials, Properties, and Devices*, Z.L. Wang, ed. (Kluwer Academic/Plenum Publishers, 2003). (Accepted for publication).

F. PRESENTATIONS STEMMING FROM RESEARCH EFFORT

December 1, 1999 – Materials Research Society 1999 Fall Meeting, Boston, MA "Growth of High Resolution Carbon Nanotube Scanning Probe Microscopy Tips by Chemical Vapor Deposition" **(Jason Hafner)**

December 13, 1999 – The Robert Maddin Lecture in Materials Science, The University of Pennyslvania, Philadelphia, PA "Nanotubes and Molecular Wires: From New Physics to New Tools for Science and Technology"
INVITED

January 24, 2000 – Nanospace 2000 – Advancing the Human Frontier, Houston, TX "Carbon Nanotube Atomic Force Microscopy Tips Produced by Chemical Vapor Deposition" **(Jason Hafner)**

March 17, 2000 – Minnesota Nanotechnology Summit: Opportunities and Challenges, Minneapolis, MN "New Tools and Devices for Nanotechnology"
INVITED

March 22, 2000 – American Physical Society March meeting 2000, Minneapolis, MN "Nanotubes and Nanowires: From New Physics to New Tools for Science and Technology"

INVITED

March 29, 2000 – American Chemical Society 219th National Meeting, San Francisco, CA "Direct Growth of Single-Walled Carbon Nanotube Scanning Probe Microscopy Tips and Application to Ultrahigh Resolution Chemical Force Microscopy and Structural Imaging" **(Chin-Li Cheung)**

April 17, 2000 NIH Single Molecule Workshop, Bethesda, MD
"Imaging and Spectroscopy at the Single Molecule Level with Carbon Nanotube Probes"
INVITED

May 8, 2000 Jet Propulsion Laboratory, Pasadena, CA "1D Nanostructures: From Fundamental Science to Building Blocks for Nanotechnologies"
INVITED

May 9, 2000 Chemical Physics Seminar Series, California Institute of Technology, Pasadena, CA "Nanocscale Wires: From Fundamental Chemistry and Physics to New Tools for Science and Technology"
INVITED

May 15, 2000 The Julia and Edward C. Lee Memorial Lecture, University of Chicago, Chicago, IL "Nanocscale Wires: From Fundamental Chemistry and Physics to New Tools for Science and Technology"
INVITED

May 28, 2000 Conference on Scanning Probe Microscopy, Sensors and Nanostructures, Heidelberg, Germany "Production of single-walled nanotube tips for biological atomic force microscopy"
(Jason Hafner)

May 29, 2000 Weizmann Institute Invited Talk, Rehovot, Israel "Nanostructures: From Fundamental Science to Building Blocks for Nanotechnologies"
INVITED

May 30, 2000 International Symposium on Nanoscience and Nanotechnology, Zichron Ya'akov, Israel "Nanoscale Wires: From Fundamental Chemistry and Physics to New tools for Science and Technology"
INVITED

August 2, 2000 Gordon Research Conference : Solid State Chemistry, New London, NH "Synthesis, Properties and Applications of Nanoscale Wires"
INVITED

August 20, 2000 220th American Chemical Society National Meeting, Washington DC "Probing Intermolecular Forces and Potentials with Magnetic Feedback Chemical Force Microscopy" **(Paul Ashby)**

August 22, 2000 220th American Chemical Society National Meeting, Washington DC "1D Nanostructures: From Fundamental Science to Building Blocks for Nanotechnologies"
INVITED

September 22, 2000 U.S. Korea Forum Nano Science and Technology, M.I.T., Cambridge, MA "Understanding and Exploiting Nanoscale Building Blocks for Nanotechnologies"
INVITED

October 2, 2000 American Vacuum Society 47th International Symposium, Boston, MA "Single Wall Nanotube Probes for Structural and Functional Imaging in Fluid" **(Liwei Chen)**

October 3, 2000 American Vacuum Society 47th International Symposium, Boston, MA "1D Nanostructures: Building Blocks for Nanotechnologies"
INVITED

October 3, 2000 American Vacuum Society 47th International Symposium, Boston, MA "Size-Dependent Mechanical Properties of MoO_3 Nanoplates" **(Jianfang Wang)**

November 3, 2000 8th Foresight Conference on Molecular Nanotechnolgoy, Washington, D.C. "Building Tools and Devices for Nanotechnology"
INVITED

November 7, 2000 Joint Research Center for Atom Technology (JRCAT) International Symposium, Tokyo, Japan "Nanotubes and Nanowires: Building Blocks for Molecular and Nanotechnologies"
INVITED

November 13, 2000 Condensed Matter Physics Seminars, University of California, Berkeley, CA "Single-walled carbon nanotubes as probes in atomic force microscopy" **(Jason Hafner)**

November 27, 2000 Materials Research Society 2000 Fall Meeting, Boston, MA "Fundamental Properties and Applications of Single-Walled Carbon Nanotubes"
INVITED

November 28, 2000 Materials Research Society 2000 Fall Meeting, Boston, MA "Individual Single-Walled Nanotube Tips for Atomic Force Microscopy" **(Jason Hafner)**

November 29, 2000 Materials Research Society 2000 Fall Meeting, Boston, MA "Imaging and Spectroscopy at the Single Molecule Level with Carbon Nanotube Probes"
INVITED

September 22, 2000 U.S. Korea Forum Nano Science and Technology, M.I.T., Cambridge, MA, "Understanding and Exploiting Nanoscale Building Blocks for Nanotechnologies"
INVITED

October 2, 2000 American Vacuum Society 47th International Symposium, Boston, MA "Single Wall Nanotube Probes for Structural and Functional Imaging in Fluid" **(Liwei Chen)**

October 3, 2000 American Vacuum Society 47th International Symposium, Boston, MA "1D Nanostructures: Building Blocks for Nanotechnologies"

INVITED

October 3, 2000 American Vacuum Society 47th International Symposium, Boston, MA "Size-Dependent Mechanical Properties of MoO_3 Nanoplates" **(Jianfang Wang)**

November 3, 2000 8th Foresight Conference on Molecular Nanotechnology, Washington, D.C. "Building Tools and Devices for Nanotechnology"
INVITED

November 7, 2000 Joint Research Center for Atom Technology (JRCAT) International Symposium, Tokyo, Japan "Nanotubes and Nanowires: Building Blocks for Molecular and Nanotechnologies"
INVITED

November 13, 2000 Condensed Matter Physics Seminars, University of California, Berkeley, CA "Single-walled carbon nanotubes as probes in atomic force microscopy" **(Jason Hafner)**

November 27, 2000 Materials Research Society 2000 Fall Meeting, Boston, MA "Fundamental Properties and Applications of Single-Walled Carbon Nanotubes"
INVITED

November 28, 2000 Materials Research Society 2000 Fall Meeting, Boston, MA "Individual Single-Walled Nanotube Tips for Atomic Force Microscopy" **(Jason Hafner)**

November 29, 2000 Materials Research Society 2000 Fall Meeting, Boston, MA "Imaging and Spectroscopy at the Single Molecule Level with Carbon Nanotube Probes"
INVITED

December 1, 2000 MIT Mildred Dresselhaus' 70th Birthday Symposium, M.I.T., Cambridge, MA "Carbon Nanotubes: Materials for Science, Teaching and Technology"
INVITED

December 11, 2000 Lectures in the Chemical Sciences (LICS) series, Harvard University, Cambridge, MA "Building and Understanding the Future with Nanoscale Science and Technology"
INVITED

February 18, 2001 45th Annual Biophysical Society Meeting, Boston, MA "Imaging and Spectroscopy of Single Molecules with Carbon Nanotube Probes"
INVITED

February 22, 2001 CeNS Winterschool 2001: Sensing and Manipulating in the Nanoworld, Mauterndorf, Austria "Nanomechanics of Carbon Nanotube Probes" **(Jason Hafner)**

March 13, 2001 APS Meeting, Seattle, Washington "Detection and imaging at the single molecule scale with carbon nanotubes" **(Jason Hafner)**
INVITED

March 26, 2001 CFMR Symposium, East Lansing, Michigan
"Nanowires and Nanotubes: Building Blocks for Nanotechnologies"
INVITED

March 28, 2001 ECS 199th Meeting, Washington, D.C. "Direct Haplotype Determination on Aligned UGT1A7 Gene Using Carbon Nanotube Probes" **(Jong-in Hahm)**

April 3, 2001 ACS San Diego National Meeting, San Diego, California
"Probing intermolecular forces and potentials with magnetic feedback chemical force microscopy" **(Paul Ashby)**

April 3, 2001 ACS San Diego National Meeting, San Diego, California
"Carbon nanotube probes: SPM probe technology for the future" **(Liwei Chen)**

May 18, 2001 5th Annual Cambridge Healthteck Institute Meeting "Advances in Assays, Molecular Labels, Signaling &Detection" Washington, DC "Direct Haplotype Determination Using Single-Walled Carbon nanotube Scanning Probe" **(Jong-In Hahm)**

May 20, 2001 NAS Nanoscience-Underlying Physical Concepts and Phenomena Meeting, Sackler Colloquium on Nanosicence, Washington DC "Nanowire and Nanotube Building Blocks for Nanoscale Science and Technology"
INVITED

May 21, 2001 California Nanosystems Institute, Nanosystems Research seminar, Santa Barbara, CA "Nanowires and Nanotubes as Building Blocks for Nanosystems"
INVITED

June 13, 2001 75th Colloid and Surface Science Symposium, Carnegie Mellon University, Pittsburgh, PA, "Imaging and Spectroscopy at the Single Molecule Level with Carbon Nanotube Probes"
INVITED

June 21, 2001 Columbia University and City University of New York, Nanostructured Materials: Present Science and Future Technology, New York, NY.
"Building the Future with Nanoscale Science and Technology"
INVITED

June 24, 2001 Gordon Research Conference on Analytical Chemistry, Connecticut College, New London, CT
"Emerging Nanoscale Materials as Molecular Scale Probes for Imaging/Sensing and as

Building Blocks for Chemical/Biological Detectors"
INVITED

June 27, 2001 National Academy of Sciences: Studies Committee, Woods Hole, MA
"Opportunities and Research Priorities for Nanoelectronics"
INVITED

July 17, 2001 11th International Conference on Scanning Tunneling Microscopy/Spectroscopy and Related Techniques (STM '01), University of British Columbia, Vancouver, Canada "High-resolution imaging with carbon nanotube AFM probes" **(Chin-li Cheung) – poster session**

July 18, 2001 11th International Conference on Scanning Tunneling Microscopy/Spectroscopy and Related Techniques (STM '01), University of British Columbia, Vancouver, Canada "Direct Haplotype Determination and SNP Mapping Using SWNT Scanning Probes" **(Jong In Hahm) – contributed talk**

August 30, 2001 NCI meeting on Nanotechnology in Early Detection of Cancer, Gaithersburg, MD "Nanotubes and Nanowires for Molecular Level Detection in Cancer"
INVITED

September 17, 2001 Physics Department Colloquium, Harvard University, Boston, MA
"Nanowires as Building Blocks for Nanoscale Science and Technology"
Invited

September 19, 2001 2nd Georgia Tech Conference on Nanoscience and Nanotechnology, Georgia Institute of Technology, Atlanta, GA
"Nanowires as Building Blocks for Nanotechnology"
Invited

October 3, 2001 Kilpatrick Lecture Series, Illinois Institute of Technology, Chicago, IL
"Nanowires as Building Blocks for Nanotechnology"
Invited

October 9, 2001 Cambridge Healthtech Institute's Fourth Annual Human Genetic Variation, Cambridge, MA
"Genetic Variations Before Your Eyes"
Invited

October 13, 2001 The Second Dartmouth Molecular Symposium, Dartmouth College, NH
"Nanowires as Building Blocks for Nanoscale Science and Technology "
Invited

October 15, 2001 Frontiers in Chemical Research, Texas A&M, College Station, TX
"Nanowire as Building Blocks for Nanoscale Science and Technology"
Invited

October 17, 2001 Frontiers in Chemical Research, Texas A&M, College Station, TX
"Biology Meets Nanotechnology: Imaging and Manipulation at the Single Molecule Scale"
Invited

October 26, 2001 APS New York Section 83rd Topical Symposium, Biophysics with Nanotechnology, U of Albany, SUNY, NY
"Carbon Nanotubes and DNA"

November 10 2001 9th Foresight Conference on Molecular Nanotechnology, Santa Clara, CA
"Nanotechnology from the Bottom Up: Building with Nanowires and Nanotubes"
Invited

November 26, 2001, MRS Fall Meeting, Boston, MA
"Diameter Controlled Growth of Carbon Nanotubes"

November 28, 2001, MRS Fall Meeting, Boston, MA
"Semiconductor Nanowires As Optoelectronic Building Blocks From Fundamental Physics to Devices"

November 29, 2001, MRS Fall Meeting, Boston, MA
"Nanowires as Building Blocks for Bottom Up Assembly Nanoscale Electronics and Optoelectronics"

November 29, 2001, MRS Fall Meeting, Boston, MA
"Carbon Nanotube SPM Probes: Fundamentals and Applications"

December 2, 2001, Philips Distinguished Visitor, Haverford College, Haverford, PA
"Nanowires as Building Blocks for Nanoscale Science and Technology"
Invited

February 11, 2002 - Cambridge Healthtech Institute Gene Quantification Conference, San Diego, CA
"Carbon Nanotube Technology in SNP and Haplotype Detection"

February 14, 2002 - American Association for the Advancement of Science Annual Meeting and Science Innovation Exposition, Nanotechnology Seminar, Boston, MA
Keynote Address: "Nanotechnology: Building a Big Future from Small Things"
Invited

April 2, 2002 – Microsystems Technology Laboratories VLSI Seminar at MIT, Cambridge, MA
"Nanowires as building blocks for Nanoelectronics and Nanophotonics"
Invited

April 11, 2002 – Gomberg Lecture, University of Michigan, Ann Arbor, MI
"Nanoscience and Nanotechnology: Building a Big Future from Small Things"
Invited

April 24, 2002 – 2002 WATT Centennial Lecture, The University of Texas at Austin, Austin TX
"Nanoscience and Nanotechnology: Building a Big Future from Small Things!"
Invited

June 24, 2002 – 7th International Conference on Nanometer-Scale Science and Technology and 21st European Conference on Surface Science, Malmö, Sweden
"Nanowire Superlattices and Core-Shell Heterostructures as Building Blocks for Nanotechnology"
Invited

July 9, 2002 – GRC Chemistry at Interfaces, Connecticut College, New London, CT,
"Nanowire- and Nanotube-Based Nanostructures"
Invited

July 11, 2002 – International Conference on the Science and Application of Nanotubes, Boston College, Chestnut Hill, MA
"Nanoscale Wires as Building Blocks for Nanoelectronics and Nanophotonics"
Invited

August 18, 2002 – 224th ACS National Meeting, Boston, MA
"Nanowires as Building Blocks for Nanoscale Science and Technology"
Invited

September 9, 2002 – 175th Anniversary of The Royal Institute of Technology at Stockholm, Stockholm, Sweden
"Building a Big Future from Small Things"
Invited

September 28, 2002 – American Physical Society Topical Conference on Opportunities in Biology for Physicists, Boston, MA
"What Can Nanotechnology do for Biology?"
Invited

November 4, 2002 – Cambridge Healthtech Institute Conference on Biodefense:Research Technologies and Applications, McLean, VA

"Highly Sensitive, Real-Time Detection of Biological and Chemical Species Using Integrated Nanowire Sensors"
(Yi Cui)

November 4, 2002 – Fudan University, Shanghai, China
"Nanoscale Science & Technology: Building a Big Future from Small Things"
Invited

November 5, 2002 – Zhu Kezhen Distinguished Lectureship, Zhejiang University, Hangzhou, China
"Nanoscale Science & Technology: Building a Big Future from Small Things"
Invited

November 5, 2002 – Zhu Kezhen Distinguished Lectureship, Zhejiang University, Hangzhou, China
"The Rich and Fundamental Electronic Properties of Carbon Nanotubes"
Invited

November 7, 2002 – University of Science and Technology of China (USTC), Hefei, China
"The Rich and Fundamental Electronic Properties of Carbon Nanotubes"
Invited

November 7, 2002 – University of Science and Technology of China (USTC), Hefei, China
"Nanoscale Science & Technology: Building a Big Future from Small Things"
Invited

November 8, 2002 - Tsinghua University, Beijing, China
"Nanoscale Science & Technology: Building a Big Future from Small Things"
Invited

November 15, 2002 – Carnegie Mellon University, Materials Science and Engineering Department Series on Electronic Materials, Pittsburgh, PA
"Nanowires as Building Blocks for Nanoelectronics and Nanophotonics"
Invited

November 21, 2002 – Massachusetts Institute of Technology, A.D. Little Lectures in Physical Chemistry, Cambridge, MA
"Nanowires as Building Blocks for Nanoscale Science and Technology"
Invited

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA
"Nanowires as Building Blocks for Nanoscale Science and Technology – Building a Big Future from Small Things"
Invited

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA
"Semiconductor Nanowire Superlattices as Building Blocks for Nanotechnology"
(Contributed Talk – Mark Gudiksen)

February 17, 2003 – Gordon Research Conference on Chemical Reaction at Surfaces, Ventura, CA
"Nanowire Building Blocks for Nanoscale Science and Technology"
Invited

March 3, 2003 – American Physical Society Conference, Austin TX
"Functional Nanostructured Materials"
Invited

G. TECHNOLOGY TRANSITIONS STEMMING FROM RESEARCH EFFORT

Our AFOSR funded research has spurred technology transitions in several specific areas. First, this work has led to the filing of three broad patents that cover nanotube tip fabrication methods and the specific application of these tips to DNA sequence analysis.

These patents are as follows:

1. C.M. Lieber, J. Hafner and C.L. Cheung, "Fabrication of Nanotube Microscopy Tips" 09/955,738, U.S. patent pending.
2. C.M. Lieber, A.T. Woolley, D.E. Housman, and J. Hahm, "Direct Haplotyping Using Carbon Nanotube Probes" 09/951,133 U.S. patent pending; PCT/US01/42138 International patent pending.
3. C.M. Lieber, J.H. Hafner, C.L. Cheung, and P. Kim "Direct Growth of Nanotubes, and Their Use in Nanotweezers" 09/966,812, U.S. patent pending; PCT/US01/30445 International patent pending.

In addition, our AFOSR funded research directed towards the new area of nanophotonics has also led to the filing of two additional patents:

1. C.M. Lieber, X. Duan, Y.Cui, Y. Huang, M.S. Gudiksen, L. Lauhon, J. Wang, H. Park, Q. Wei, W. Liang, D.C. Smith, D. Wang and Z. Zhong, "Nanoscale Wires and Related Devices", 10/196,337, U.S. patent pending; PCT/US02/16133, International patent pending.
2. C.M. Lieber, X. Duan, Y. Huang, and R. Agarwal, "Nanoscale Coherent Optical Components", 60/397,121, U.S. provisional patent pending.
3. C.M. Lieber, H. Park, Q. Wei, Y. Cui, and W. Liang, "Nanosensors", 10/020,004, U.S. patent pending; PCT/US01/48230, International patent pending.

Significantly, these patents have been licensed by Nanosys, Inc., which is a new start-up company focused on the commercialization of nanotechnology. In addition, we have

executed a formal research agreement with Intel Corporation to investigate commercial applications of nanowire devices, and are in process of negotiating a research agreement Applied Biosystems, Inc. (ABI) on nanowires based detector/sensor devices for biology.

H. HONORS AND AWARDS EARNED DURING AWARD PERIOD
Nelson W. Taylor Award (2003);

World Technology Award in Materials (2003);

New York Intellectual Property Law Association Inventor of the Year (2003);

APS McGroddy Prize for New Materials (2003)

Honorary Professorship, Tsinghua University (2002)

Honorary Professorship, University of Science and Technology of China (2002)

Honorary Professorship, Fudan University (2002)

Honorary Professorship, Zhejiang University (2002),

Elected Member, American Academy of Arts and Sciences (2002).

2002 Materials Research Society MRS Medal for exceptional achievements in materials research (2002)

Fellow of the World Technology Network (2002)

Feynman Prize in Nanotechnology, Foresight Institute (2001)

Editorial Board, Applied Physics Letters.

Editorial Board, Journal of Applied Physics.

Editorial Board, Journal of Nanoscience and Nanotechnology.

Editorial Board, Journal of Physical Chemistry.

Advisory Editorial Board, Journal of Physics: Condensed Matter.

Editorial Board, NanoLetters.

Editorial Board, Virtual Journal of Nanoscale Science and Technology, American Institute of Physics

Advisory Board, Advances in Nanoscale Materials and Nanotechnology, book series.

Editorial Advisory Board, Encyclopedia of Nanoscience and Nanotechnology, Fullerenes, Nanotubes and Carbon Nanostructures.

Advisory Board, Nanotechnology Opportunity Report.